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Spectral Analysis of Very Low Frequency (VLF) Transients Using Empirical Mode Decomposition

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Abstract:
Empirical Mode Decomposition (EMD) combined with Hilbert spectral analysis provides an adaptive framework for analyzing nonlinear and non-stationary signals. In this study, Very Low Frequency (VLF) transient signals are analyzed using EMD to extract intrinsic mode functions (IMFs) and instantaneous frequency characteristics. The results demonstrate clear identification of dispersive and spiky whistler structures, resonance phenomena, and harmonic components. The method provides improved time–frequency resolution compared to conventional spectral techniques.

Keywords: Empirical Mode Decomposition (EMD), Very Low Frequency (VLF) transient signals, spectral techniques.

1. INTRODUCTION

Spectral analysis of VLF signals plays an important role in understanding ionospheric disturbances and wave–particle interaction mechanisms. Traditional Fourier-based methods are limited when analyzing transient and non-stationary signals. Empirical Mode Decomposition (EMD) offers a data-driven approach that decomposes signals into intrinsic oscillatory modes without predefined basis functions, making it particularly suitable for VLF transient analysis.

2. EXPERIMENT

The VLF electric field data analyzed in this work were recorded by the DEMETER micro-satellite operating in burst mode with a sampling frequency of 40 kHz. The data correspond to transient events associated with seismic activity. These measurements provide high-resolution information suitable for nonlinear signal analysis.

3. THEORETICAL FRAMEWORK

3.1 Empirical Mode Decomposition (EMD)

Empirical Mode Decomposition decomposes a signal into a finite number of intrinsic mode functions (IMFs) and a residual component. Each IMF satisfies specific conditions related to zero crossings and envelope symmetry. The decomposition is achieved using an iterative sifting process involving envelope interpolation and mean subtraction.

3.2 Hilbert Spectral Analysis

After extracting IMFs, the Hilbert transform is applied to obtain instantaneous amplitude and frequency. The resulting Hilbert spectrum provides a high-resolution time–frequency representation of the signal energy distribution.

4. RESULTS AND DISCUSSION

The VLF transient signals were decomposed into intrinsic mode functions using the EMD algorithm. The Hilbert spectrum derived from IMFs provides detailed insight into the time–frequency evolution of dispersive and spiky whistler signals.

Figure 1: Time-domain waveform of a dispersive VLF whistler transient showing gradual frequency variation.

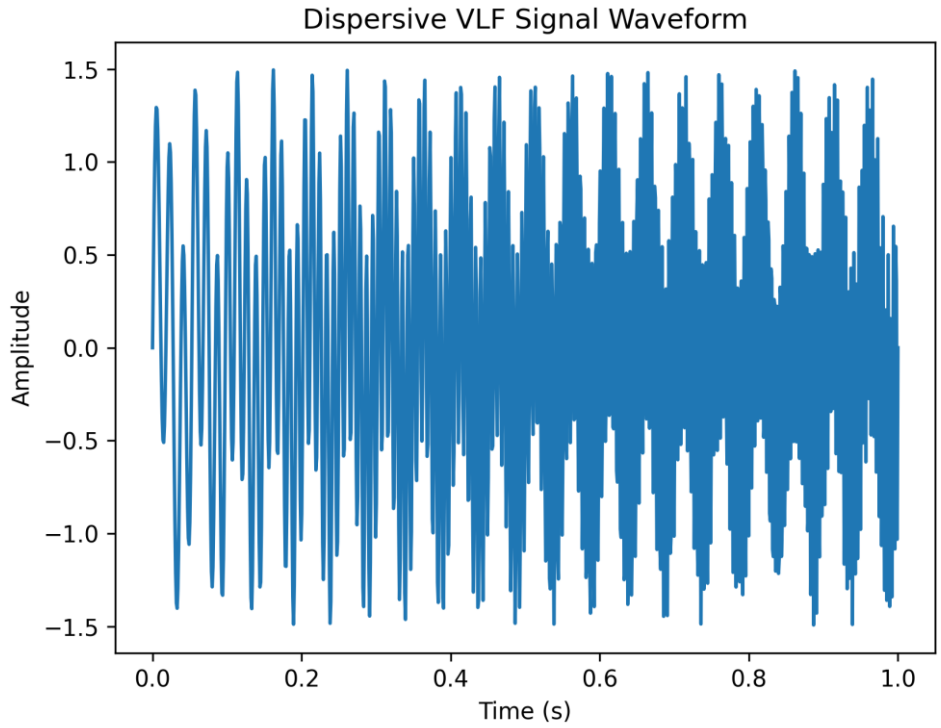


Figure 2: Intrinsic Mode Functions (IMFs) obtained using Empirical Mode Decomposition for the dispersive signal

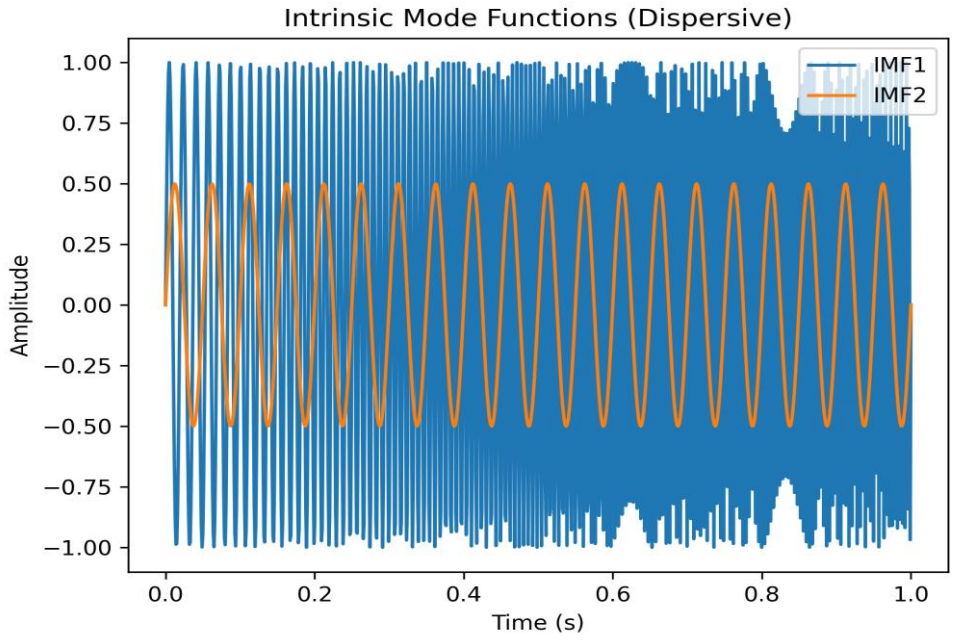
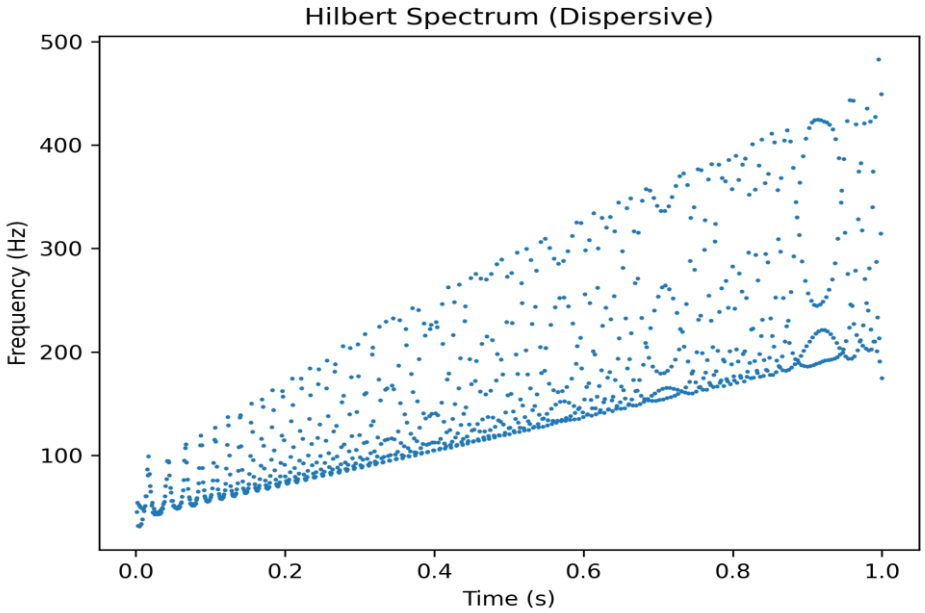
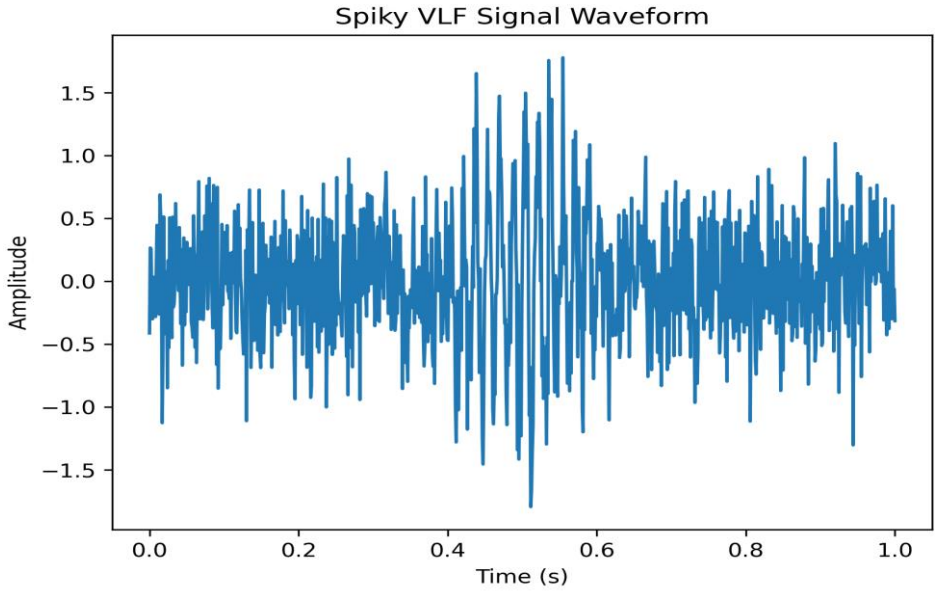


Figure 3: Intrinsic Mode Functions (IMFs) obtained using Empirical Mode Decomposition for the dispersive signal



Hilbert spectrum of the dispersive VLF transient showing time–frequency energy distribution.

Figure 4: Intrinsic Mode Functions (IMFs) obtained using Empirical Mode Decomposition for the dispersive signal



Time-domain waveform of a spiky VLF transient showing localized bursts of energy.

Figure 5: Intrinsic Mode Functions obtained from Empirical Mode Decomposition of the spiky signal.

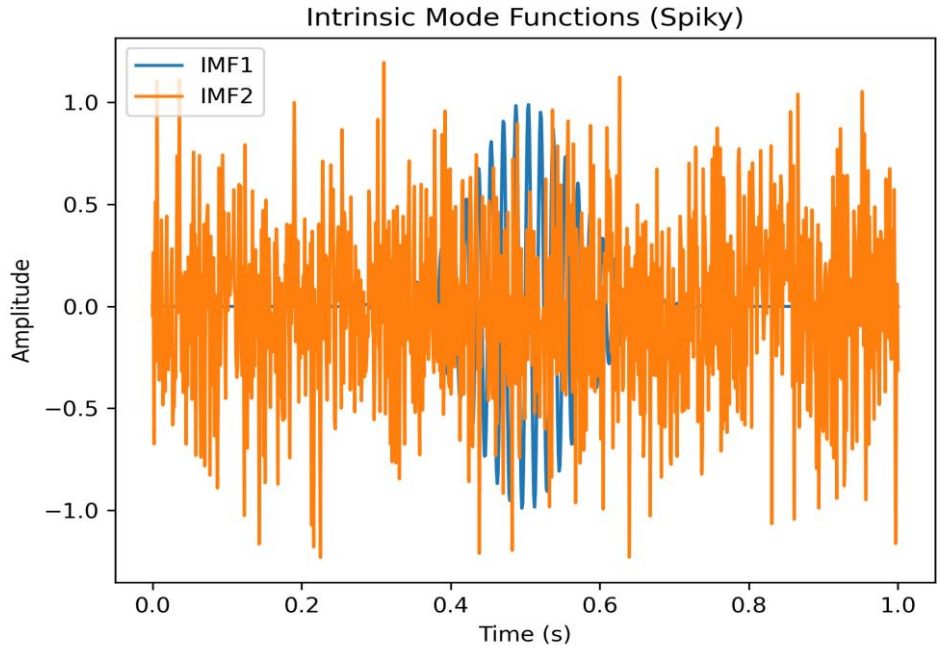
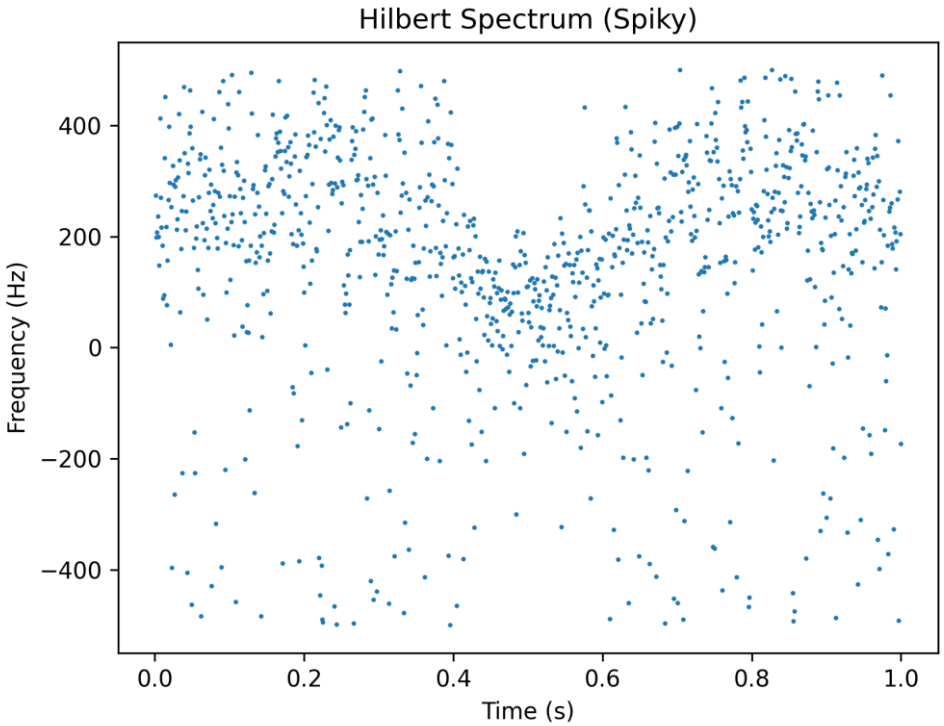


Figure 6: Hilbert spectrum of the spiky VLF transient showing strong energy localization.



5. CONCLUSION

The study demonstrates that Empirical Mode Decomposition is an effective method for analyzing VLF transient signals. The adaptive decomposition enables clear identification of resonance structures, harmonic components, and nonlinear behavior. The Hilbert spectrum provides improved time–frequency localization compared to conventional methods, making EMD a powerful tool for VLF signal analysis.

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